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Fire hazards of façade materials for energy conservation under flashover

W.K. Chow*, J. Liu

Department of Building Services Engineering, The Hong Kong Polytechnic University
Hong Kong, China

Abstract

Several fires had occurred in air-conditioned double-deck buses with energy-conserving façade foam materials in the past few years. Citizens in Hong Kong are now worrying whether they are safe while staying inside enclosures with energy-conserving foam materials. There are very few studies on evaluating the fire performance of façade materials. Solar heat gain control by using Overall Thermal Transfer Value in buildings would give shorter time to flashover. Flashover is hazardous in a room for fires with a sharp increase in burning rate and gas temperature. In this paper, nonlinear dynamics was used to study flashover in an example room using a two-layer zone model. A differential equation was set up to describe the rate of change of the layer temperature based on simple heat balance of the smoke layer. Evolution of the smoke layer temperature, equilibrium states of the system and their corresponding stabilities were then investigated.

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Keywords: Foam façade materials; fire behaviour, high heat flux, nonliner dynamical system

1. Introduction

More and more tall buildings have sprung up due to limited land resources, especially in densely populated areas [1]. Tall commercial buildings in big cities of the Asian-Oceanian regions are enclosed with indoor environment controlled by mechanical ventilation and air-conditioning system [2]. Building façade was then designed with better thermal insulation to minimize solar heat gain. Energy code on Overall Thermal Transfer Value (OTTV) [3] set up

* Corresponding author. Tel.: +852 2766 5843 ; fax: +852 2765 7198.
E-mail address: beelize@polyu.edu.hk; bewkchow@polyu.edu.hk

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on limiting solar heat gain through building façade in Hong Kong is an example. The OTTV is used to describe the maximum thermal transfer permissible into the building through its wall or roof, due to solar heat gain and outdoor-indoor temperature difference. However, big fire hazards in these tall buildings had attracted attention on fire safety. New fire hazards were experienced in such new building design features [1]. For example, several new façade materials developed for reducing solar heat gain already gave short time to flashover. A small fire in an enclosure with good insulating façade materials would trap heat and mass emitted. A very rapid and sudden transition from a growing fire to a fully developed fire would take place with flashover occurring in a short time. Consequently, the fire could become more catastrophic as experienced in many air-conditioned double-deck bus fires before with one occurred recently [4]. Further, the fire load density in some residential buildings was reported to be extremely high and can be burnt up if ventilation provision is adequate.

Flashover is hazardous in a room for fires with a sharp increase in burning rate and gas temperature. Thermal instability is considered to be one of the mechanisms of flashover [5]. In this paper, the potential flashover hazard with new façade materials will be discussed using nonlinear dynamics [e.g. 6-8] in an example room. A two-layer zone model was used to simulate the room fire by a hot upper smoke layer and a cool lower layer. A differential equation was set up to describe the rate of change of the layer temperature based on simple heat balance of the smoke layer. The effect of different façade materials on the critical conditions for flashover was then examined.

2. The example room

Flashover in an example room [7] as shown in Fig. 1 was examined by nonlinear dynamics. A single rectangular vent was located at the center of one wall. A fire source was centered at the floor level. The process of the room fire was considered as a dynamical system. Based on a two-layer zone model, the nonlinear dynamical analysis was carried out by assuming [7] that the density of the smoke layer ρ_0 was constant. Temperature of the lower air layer and its bounding surfaces were kept at the initial value T_0. The emissivity of the fire source and smoke layer were assumed to be 1. The surface of the wall was assumed to be black body. Before flashover, the fire was assumed [6,7] to be burning with the height of the smoke layer interface kept at a constant value of 0.5 H. The height of the neutral plane coincided with the height of the smoke layer interface. In the ventilation-controlled stage, the air entering into the room was assumed to be completely consumed.

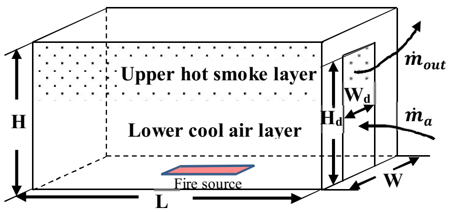


Fig. 1. Schematic of the example room.

The evolution equation for this fire dynamical system is developed based on the energy conservation [e.g. 8] for the upper hot smoke layer:

$$m \cdot c_p \cdot \frac{dT}{dt} = G_E - L_E \tag{1}$$

The left hand side of equation (1) is the energy change rate of the smoke layer. m is the mass of the smoke layer; c_p is the specific heat capacity (at constant pressure); T is the average temperature of the hot smoke layer and t is time. On the right hand side, G_E and L_E are net heat gain rate and net loss rate of the hot smoke layer respectively. Both are functions of smoke layer temperature.

The heat gain rate of the smoke layer G_E is determined by the convection fraction of the heat released by the fire $\dot{Q}$ that goes into the upper smoke layer. χ_R is the fraction of energy loss due to radiation from the flames.

$$G_E = (1-\chi_R)\cdot\dot{Q} \tag{2}$$

In a compartment fire, thermal radiation feedback from the hot smoke layer and heated boundary surfaces to the fuel surfaces has been recognized as playing an important role in the onset of flashover. In this model, the radiation feedback $\dot{R}_{in}$ is calculated based on a considerably simplified formula. Actually, it is affected by emissivity and temperature of the smoke layer and wall surfaces, and their view factors to the fuel surface.

$$\dot{R}_{in} = \mu\cdot\sigma\cdot(T^4 - T_0^4)L\cdot W \tag{3}$$

Where L and W are the length and width of the room respectively; σ is the Stefan-Boltzmann constant; μ is the radiant feedback coefficient; and T_0 is the ambient temperature.

In a ventilation-controlled fire, the gas temperature is most often very high and the smoke gas is roughly mixed evenly. A simplified expression can be used to obtain the mass flow rate of air into the compartment through the opening of width W_d and height H_d:

$$\dot{m}_a = 0.5\cdot W_d\cdot H_d^{1.5} \tag{4}$$

The total heat loss from the hot smoke layer L_E due to mass flow through the opening, conduction loss to the compartment boundary and radiation loss to the opening can be expressed by the following formula:

$$\begin{aligned} L_E &= \sigma(T^4 - T_0^4)[LW + W_d(H_d - Z)] + A_w\sigma(T^4 - T_w^4) \\ &\quad + A_w h_t(T - T_w) + c_p\dot{m}_{out}(T - T_0) \\ A_w &= LW + (2L + 2W - W_d)(H - Z) + (H - H_d)W_d \end{aligned} \tag{5}$$

Here, T_w is the surface temperature of the upper parts of the walls bounding the hot smoke gas; A_w is the area of the solid boundary enclosing the hot smoke layer; z is the height of the smoke layer interface from the floor level; and h_t is the convective heat transfer coefficient. In equation (5), there are four items on the right hand side. The first item is the radiative heat loss from the smoke layer to the lower part of the compartment and the vent; the second and the third items are heat lost to the solid boundaries enclosing the hot smoke by radiation and convection respectively; and the forth item is the enthalpy flowing out through the vent. The outflow $\dot{m}_{out}$ driven by buoyancy through the vent can be estimated [6,7].

For simplicity, the surface temperature of the heated walls T_w is approximated as a fraction of the smoke layer temperature [8]:

$$T_w = U_c(T - T_0) + T_0 \tag{6}$$

Where U_c is a wall temperature parameter ranging from 0 to 1, which depends on thermal inertia properties of the wall material. The surface temperature of a material with a low thermal inertia, like polyurethane foam, rises quickly when exposed to heat.

In this paper, the smoke layer temperature T was taken as the single state variable. The other parameters acted as control parameters. At critical parameter values, the system state will undergo qualitative and violent change which is called bifurcations [6-8]. A local bifurcation occurs when parameter changes cause an equilibrium point to lose its stability. The equilibrium points are points where the rates of change of the state variables become zero. The stability can be determined by its eigenvalues of the constant Jacobian matrix. The equilibrium point is stable if all corresponding eigenvalues are negative and if not, then unstable. Bifurcation may occur where the eigenvalue is zero. When bifurcation occurs, the system jumps from the current equilibrium state to a new remote one and flashover is deemed to happen. According to the dynamical theory, the critical conditions for flashover are:

$$\frac{dT}{dt} = 0 \quad \text{and} \quad \lambda = \frac{\partial}{\partial T}\frac{dT}{dt}\bigg|_{T=T_{equ}} = 0 \tag{7}$$

T_{equ} represents equilibrium points of the system and λ denotes the eigenvalues.

3. Effect of the façade material

The effect of wall material on the fire process is incorporated into the model by the wall temperature parameter U_c in equation (6). But for a given wall material, its thermal properties should be considered in the heat transfer process. As reviewed by Chow [9] before, heat lost through the façade material Q_L (in W) can be roughly proportional to the room temperature rise ΔT (in °C) over the initial wall temperature T_0 through the effective heat transfer coefficient h_c (in Wm^{-2}K^{-1}) and the surface area A_w (in m^2) of the façade:

$$Q_L = h_c \cdot A_w \cdot (T - T_0) \tag{8}$$

In view of equation (5), the second and the third items on the right hand side which indicate heat lost to the solid boundaries enclosing the hot smoke by radiation and convection can be replaced by the following expression:

$$Q_L = h_c \cdot (T - T_0) \cdot [L \cdot W + (2L + 2W - W_d)(H - Z) + (H - H_d)W_d] \tag{9}$$

The effective heat transfer coefficient of the wall h_c at exposure time t is expressed in terms of the thermal conductivity k_w (in Wm^{-1}K^{-1}), density ρ_w (in kgm^{-3}), specific heat capacity c_w (in Jkg^{-1}K^{-1}) and thickness d_w (in m) of the wall:

$$h_c = C_1 Max\left\{\left(\frac{k_w \rho_w c_w}{t}\right)^{0.5}, \frac{k_w}{d_w}\right\} \tag{10}$$

Note that this equation was derived from studying thermal conduction in a semi-infinite solid. Value of C_1 is reported by Deal and Beyler [10] to be 0.4 for compartment fires. Typical values of thermal properties together with the steady-state value of h_c (thickness of the material is assumed to be 0.01 m) for common building materials, such as glass and steel, are shown [9,11] in Table 1. Properties of other building materials such as concrete are shown as well for comparison.

Table 1. Typical values for thermal properties of wall materials and critical conditions for flashover.

Materials	Thermal conductivity k_w / Wm^{-1}K^{-1}	Density ρ_w / kgm^{-3}	Specific heat capacity c_w / Jkg^{-1}K^{-1}	Thermal inertia $k_w\rho_w c_w$ / (Wm^{-2}K^{-1})^{2}s^{-1}	Steady state effective heat transfer coefficient h_c / Wm^{-2}K^{-1}	Critical heat release rate Q / kW	Critical temperature T / K
Polyurethane foam	0.034	20	1400	950	1.4	958	534
Glass fibers with organic bonds	0.038	32	835	1015	1.5	960	534
Timber	0.12	540	2500	1.62×10^5	4.8	1076	545
Gympsum plaster	0.8	1700	840	1.14×10^6	32	2168	622
Glass	1.2	2500	750	2.25×10^6	48	2902	659
Concrete	1.6	2400	750	2.88×10^6	64	3715	694
Steel	48	7854	559	2.11×10^8	1920	254563	1839

Based on the model developed, the effect of façade material on the critical condition for flashover was examined in an example room of length 6 m, width 3.5 m and height 3 m. The selected values of control parameters and constants used are: σ of $5.67 \cdot 10^{-8}$ Wm^{-2}K^{-4}, c_p of 1003.2 J/kg K, C_d of 0.7, g of 9.81 m s^{-2}, h_t of 7 Wm^{-2} K^{-1}W/m^{2}K, H_{com} of $4.2 \cdot 10^7$ J /kg, H_d of 3 m, H_{vap} of $1.008 \cdot 10^6$J/kg, r of 30, T_0 of 300 K, U_c of 0.7, W_d of 1 m, Z of 1.5 m, χ of 1, χ_R of 1/3, μ of 0.15 and ρ_0 of 1.18 kg·m^{-3}.

4. Results

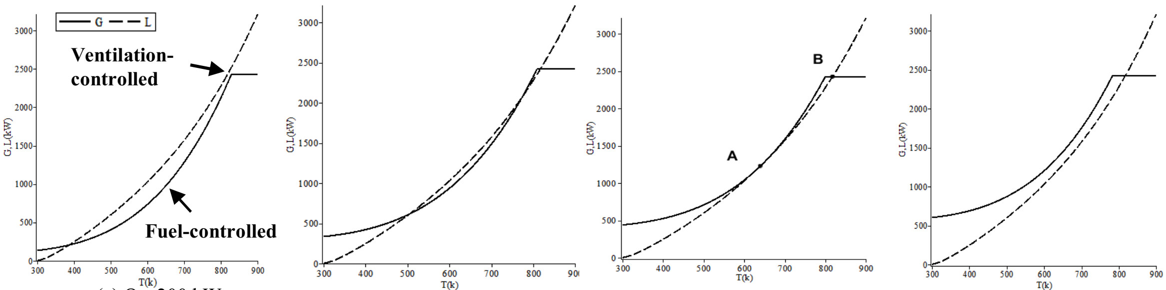
The heat gain rate and loss rate curves of the smoke layer were plotted against temperature. As the fire grew, which can be represented by the increasing Q_0 values, it was found that there were four typical relative positions for G and L curves. As demonstrated in Fig. 2a to d, there may be one, two, or three intersections. These intersections denote equilibrium states. The stability of the equilibrium points can be determined by its corresponding eigenvalues in Fig. 2b. When the fire is small, there is only one intersection and the fire will stabilize at a lower temperature. As shown in Fig. 2b, there are two intersections in the growth stage. The higher temperature point is unstable and does not exist physically. In Fig. 2c, the two curves are tangent at point A (corresponding to points C, E respectively). A small increment in temperature will cause the smoke layer temperature to rise rapidly to point B (corresponding to points D, F respectively) which represents a ventilation-controlled state. This jump from an equilibrium state to another remote stable state is called bifurcation which is considered as the occurrence of flashover. The eigenvalue for point C is zero which can be seen from Fig 3b. This rapid transition is demonstrated more vividly in Fig. 3a. With the increase of heat release rate, the smoke layer temperature jumps from point C to point D. In Fig. 2d, the heat gain rate curve is always above the heat loss rate curve, so the fire can grow continually to the ventilation-controlled stage.

In the model developed, the occurrence of flashover has a close relationship with the heat gain rate and loss rate of the smoke layer. The temperature of the wall has an effect on how much heat will be dissipated through the solid boundary and its value depends on the thermal properties of the wall materials. If the thermal inertia of the wall is low, the wall surface heats quickly and U_c is indicated by a large value. If the thermal inertia is of a higher value, the wall surface heats slowly, then a small U_c is used. Critical heat release rate for flashover under varying values of U_c can be predicted as in Fig. 3c. With the increase of U_c, the critical heat release rate for the occurrence of flashover in the example room reduces. In the extreme case where U_c=0.0, a big value of heat release rate, about 5 MW, is needed to initiate flashover. According to the model, the maximum heat release rate that can be achieved is about 3.6 MW, and then if the thermal inertia of the material is too big, flashover may not happen. When U_c=1.0, little heat is dissipated away through the solid boundary and more heat is trapped in the enclosure. Flashover will take place more likely and quickly.

To consider the effect of certain type of façade material on the critical conditions for flashover, ceiling and walls are assumed to be made of the same kind of material. Equation (5) is substituted by equation (8) in the nonlinear model and for simplification, the conduction heat transfer through the solid boundary with a thickness of 0.01 m is presumed to reach a steady state. The critical conditions for flashover calculated by the model are listed in Table 1. It is obvious that compared with materials with large thermal inertia like steel, flashover is more likely to occur when the room is enclosed with materials like glass fibers with organic bonds and timber.

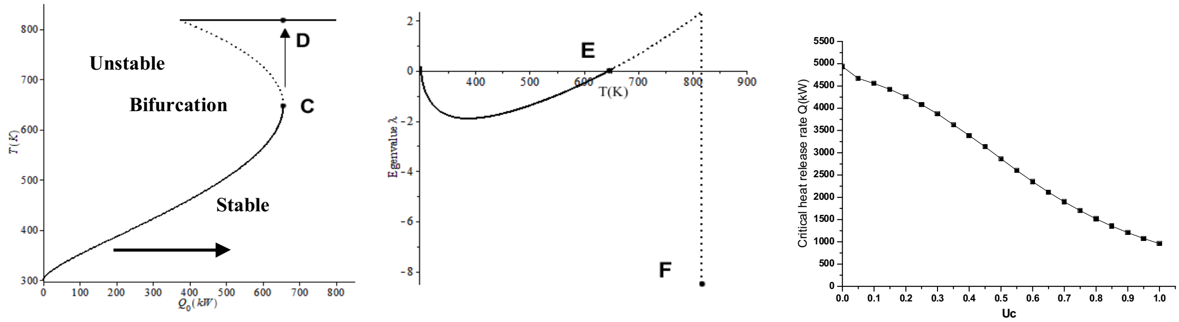
5. Conclusions

As the cooling load strongly depends on the construction of the building envelope and the weather conditions, limiting the amount of solar heat gain through these building envelopes is obviously an important step for minimizing the cooling energy consumption. In practice, building façade usually involves a composite of materials, other than a single layer of certain material. In this study, the effect of individual façade material on flashover is emphasized. Though the façade modeled differs from the real configurations, it can demonstrate the fire risk associated with building façade featured energy conservation in a simple way. When materials with better thermal insulation, like foam or glass materials, are used for energy conservation in air-conditioned buildings, heat generated from a fire will be trapped and flashover would occur easily. On the other hand, a fire in a building made of steel would burn with a longer time to flashover. Therefore when designing building façade, the effect of materials used on fire development should be taken into account.



(a) Q_0=200 kW (b) Q_0=500 kW (c) Q_0=656 kW (d) Q_0=900 kW

Fig. 2. Demonstration of flashover occurrence.



(a) Demonstration of bifurcation occurrence (b) Eigenvalues (c) Critical heat release rate for flashover

Fig. 3. Nonlinear dynamics theory.

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